Claims

1. Method of determining an average charge state, $\overline{q}$, of cluster ions in a cluster ion beam having a beam path within a reduced-pressure chamber, comprising the steps of:

providing, within the reduced-pressure chamber, a cluster ion beam attenuator, a particle flow rate measurement means, and a cluster ion beam current measurement means;

disposing the cluster ion beam attenuator within the path of said cluster ion beam to form an attenuated sample of the cluster ion beam;

measuring, in turn, the particle flow rate, Γ, of the attenuated sample of the cluster ion beam and the cluster ion beam current, I, of the attenuated sample of the cluster ion beam; and

calculating a measure of the average charge state, $\overline{q}$, of cluster ions in the cluster ion beam by using the equation

$$\overline{q} = \frac{\alpha I}{\beta e \Gamma}$$

wherein α and β are calibration constants and e is the magnitude of the electronic charge.

2. The method of claim 1, wherein the particle flow rate measurement is performed prior to the cluster ion beam current measurement.

3. The method of claim 1, wherein the particle flow rate measurement is performed after the cluster ion beam current measurement.

4. The method of claim 1, further comprising the step of:

predetermining the calibration constants α and β, wherein α is a detection efficiency of the beam current measurement means and β is a detection efficiency of the particle flow rate measurement means.

5. The method of claim 1, further comprising the step of:

removing the cluster ion beam attenuator from the cluster ion beam path.

6. The method of claim 5, further comprising the step of:

using the determined average charge state, $\overline{q}$, of cluster ions in the cluster ion beam to control the adjustment of cluster ion beam parameters.

7. The method of claim 5, wherein the cluster ion beam is a gas cluster ion beam.

8. Method of determining an average mass, $\overline{m}$, of cluster ions in a cluster ion beam having a beam path within a reduced-pressure chamber, comprising the steps of:

providing, within the reduced-pressure chamber, an average energy per charge measurement means, an average velocity measurement means , a particle flow rate measurement means, and a cluster ion beam current measurement means;

disposing the cluster ion beam attenuator within the path of said cluster ion beam to form an attenuated sample of the cluster ion beam;

measuring, in turn but in any order, the particle flow rate, Γ, of the attenuated sample of the cluster ion beam, and the cluster ion beam current, I, of the attenuated sample of the cluster ion beam, and the average energy per charge, $\left(\frac{E}{q}\right)_{average}$, of the

cluster ions in the attenuated sample of the cluster ion beam, and the average velocity, $\overline{v}$, of the cluster ions in the attenuated sample of the cluster ion beam; and

calculating a measure of the average mass, $\overline{m}$, of cluster ions in the cluster ion beam by using the equations

$$\overline{q} = \frac{\alpha I}{\beta e \Gamma},$$

$$\overline{E} = \overline{q}\left(\frac{E}{q}\right)_{average}, \text{ and}$$

$$\overline{m} = \frac{2\overline{E}}{\overline{v}^2},$$

wherein α and β are calibration constants and e is the magnitude of the electronic charge.

9. The method of claim 8, further comprising the step of:

predetermining the calibration constants α and β, wherein α is a detection efficiency of the beam current measurement means and β is a detection efficiency of the particle flow rate measurement means.

10. The method of claim 8, further comprising the step of:

removing the cluster ion beam attenuator from the cluster ion beam path.

11. The method of claim 10, further comprising the step of:

using the determined average mass, $\overline{m}$, of cluster ions in the cluster ion beam to control the adjustment of cluster ion beam parameters.

12. The method of claim 10, wherein the cluster ion beam is a gas cluster ion beam.

13. Method of determining an average energy, $\overline{E}$, of cluster ions in a cluster ion beam having a beam path within a reduced-pressure chamber, comprising the steps of:

providing, within the reduced-pressure chamber, an average energy per charge measurement means, a particle flow rate measurement means, and a cluster ion beam current measurement means;

disposing the cluster ion beam attenuator within the path of said cluster ion beam to form an attenuated sample of the cluster ion beam;

measuring, in turn but in any order, the particle flow rate, Γ, of the attenuated sample of the cluster ion beam, and the cluster ion beam current, I, of the attenuated sample of the cluster ion beam, and the average energy per charge, $\left(\frac{E}{q}\right)_{average}$, of the cluster ions in the attenuated sample of the cluster ion beam; and

calculating a measure of the average energy, $\overline{E}$, of cluster ions in the cluster ion beam by using the equations

$$\overline{q} = \frac{\alpha I}{\beta e \Gamma}, \text{ and}$$

$$\overline{E} = \overline{q}\left(\frac{E}{q}\right)_{average},$$

wherein α and β are calibration constants and e is the magnitude of the electronic charge.

14. The method of claim 13, further comprising the step of:

predetermining the calibration constants α and β, wherein α is a detection efficiency of the beam current measurement means and β is a detection efficiency of the particle flow rate measurement means.

15. The method of claim 13, further comprising the step of:

removing the cluster ion beam attenuator from within the cluster ion beam path.

16. The method of claim 15, further comprising the step of:

using the determined average energy, $\overline{E}$, of cluster ions in the cluster ion beam to control the adjustment of cluster ion beam parameters.

17. The method of claim 15, wherein the cluster ion beam is a gas cluster ion beam.

18. Method of determining an average mass, $\overline{m}$, of cluster ions in a cluster ion beam having a beam path within a reduced-pressure chamber, comprising the steps of:

providing, within the reduced-pressure chamber, an average energy per charge measurement means, an average mass per charge measurement means, a particle flow rate measurement means, and a cluster ion beam current measurement means;

disposing the cluster ion beam attenuator within the path of said cluster ion beam to form an attenuated sample of the cluster ion beam;

measuring, in turn but in any order, the particle flow rate, Γ, of the attenuated sample of the cluster ion beam and the cluster ion beam current, I, of the attenuated sample of the cluster ion beam and the average energy per charge, $\left(\frac{E}{q}\right)_{average}$, of the

cluster ions in the attenuated sample of the cluster ion beam, and the average mass per charge, $\left(\frac{m}{q}\right)_{average}$, of the cluster ions in the attenuated sample of the cluster ion beam; and

calculating a measure of the average mass, $\overline{m}$, of cluster ions in the cluster ion beam by using the equations

$$\overline{q} = \frac{\alpha I}{\beta e \Gamma}, \text{ and}$$

$$\overline{E} = \overline{q}\left(\frac{E}{q}\right)_{average}, \text{ and}$$

$$\overline{m} = \overline{q}\left(\frac{m}{q}\right)_{average},$$

wherein α and β are calibration constants and e is the magnitude of the electronic charge.

19. The method of claim 18, further comprising the step of:

predetermining the calibration constants α and β, wherein α is a detection efficiency of the beam current measurement means and β is a detection efficiency of the particle flow rate measurement means.

20. The method of claim 18, further comprising the step of:

removing the cluster ion beam attenuator from within the cluster ion beam path.

21. The method of claim 20, further comprising the step of:

using the determined average mass, $\overline{m}$, of cluster ions in the cluster ion beam to control the adjustment of cluster ion beam parameters.

22. The method of claim 20, wherein the cluster ion beam is a gas cluster ion beam.

23. An apparatus utilizing a gas cluster ion beam for processing a surface of a workpiece, the apparatus comprising:

a vacuum vessel;

a gas cluster ion beam source within the vacuum vessel for producing a gas cluster ion beam;

an accelerator for accelerating the gas cluster ion beam along a beam path;

workpiece holding means within the vacuum vessel for holding the workpiece for gas cluster ion beam processing;

first controllable moving means for selectively scanning said workpiece holding means and the workpiece through said accelerated gas cluster ion beam at a location along said beam path and for selectively removing the workpiece holding means and the workpiece from said gas cluster ion beam path;

a cluster ion beam attenuator within said vacuum vessel with second controllable moving means for selectively positioning said attenuator within the gas cluster ion beam path for forming an attenuated sample of the gas cluster ion beam or for positioning said attenuator away from said gas cluster ion beam path for allowing workpiece processing by the un-attenuated gas cluster ion beam;

cluster ion beam current measurement means for measuring a current, I, of said attenuated sample of the gas cluster ion beam;

particle flow rate measurement means for measuring a particle flow rate, Γ, of said attenuated sample of the gas cluster ion beam;

time-of-flight measurement means for measuring an average velocity, $\bar{v}$, of cluster ions in said attenuated sample of the gas cluster ion beam;

spectrometer means for measuring an average energy per charge, $\left(\frac{E}{q}\right)_{average}$, of the cluster ions in the attenuated sample of the cluster ion beam;

calculating means for processing measurements of $\left(\frac{E}{q}\right)_{average}$, I, Γ, and $\bar{v}$, to calculate a measure of an average mass, $\overline{m}$, of cluster ions in the gas cluster ion beam; and

control means for providing signals to said first and second controllable moving means for positioning the attenuator within the gas cluster ion beam path for making average mass, $\overline{m}$, measurement and also for positioning the attenuator away from said gas cluster ion beam path and for scanning the workpiece through said gas cluster ion beam path for workpiece processing.

24. The apparatus of claim 23, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average mass, $\overline{m}$, of clusters in the gas cluster ion beam to control the production of the gas cluster ion beam to improve the workpiece processing.

25. The apparatus of claim 23, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average mass, $\overline{m}$, of clusters in the gas cluster ion beam to adjust the average mass, $\overline{m}$, of clusters in the gas cluster ion beam to a desired value.

26. An apparatus utilizing a gas cluster ion beam for processing a surface of a workpiece, the apparatus comprising:

a vacuum vessel;

a gas cluster ion beam source within the vacuum vessel for producing a gas cluster ion beam;

an accelerator for accelerating the gas cluster ion beam along a beam path;

workpiece holding means within the vacuum vessel for holding the workpiece for gas cluster ion beam processing;

first controllable moving means for selectively scanning said workpiece holding means and the workpiece through said accelerated gas cluster ion beam at a location along said beam path and for selectively removing the workpiece holding means and the workpiece from said gas cluster ion beam path;

a cluster ion beam attenuator within said vacuum vessel with second controllable moving means for selectively positioning said attenuator within the gas cluster ion beam path for forming an attenuated sample of the gas cluster ion beam or for positioning said attenuator away from said gas cluster ion beam path for allowing workpiece processing by the un-attenuated gas cluster ion beam;

cluster ion beam current measurement means for measuring a current, I, of said attenuated sample of the gas cluster ion beam;

particle flow rate measurement means for measuring a particle flow rate, Γ, of said attenuated sample of the gas cluster ion beam;

time-of-flight measurement means for measuring an average velocity, $\bar{v}$, of cluster ions in said attenuated sample of the gas cluster ion beam;

spectrometer means for measuring an average energy per charge, $\left(\frac{E}{q}\right)_{average}$, of the cluster ions in the attenuated sample of the cluster ion beam;

calculating means for processing measurements of $\left(\frac{E}{q}\right)_{average}$, I, Γ, and $\bar{v}$, to calculate a measure of an average energy, $\bar{E}$, of cluster ions in the gas cluster ion beam; and

control means for providing signals to said first and second controllable moving means for positioning the attenuator within the gas cluster ion beam path for making average energy, $\bar{E}$, measurement and also for positioning the attenuator away from said gas cluster ion beam path and for scanning the workpiece through said gas cluster ion beam path for workpiece processing.

27. The apparatus of claim 26, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average

energy, $\overline{E}$, of clusters in the gas cluster ion beam to control the production of the gas cluster ion beam to improve the workpiece processing.

28. The apparatus of claim 26, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average energy, $\overline{E}$, of clusters in the gas cluster ion beam to adjust the average energy, $\overline{E}$, of clusters in the gas cluster ion beam to a desired value.

29. An apparatus utilizing a gas cluster ion beam for processing a surface of a workpiece, the apparatus comprising:

a vacuum vessel;

a gas cluster ion beam source within the vacuum vessel for producing a gas cluster ion beam;

an accelerator for accelerating the gas cluster ion beam along a beam path;

workpiece holding means within the vacuum vessel for holding the workpiece for gas cluster ion beam processing;

first controllable moving means for selectively scanning said workpiece holding means and the workpiece through said accelerated gas cluster ion beam at a location along said beam path and for selectively removing the workpiece holding means and the workpiece from said gas cluster ion beam path;

a cluster ion beam attenuator within said vacuum vessel with second controllable moving means for selectively positioning said attenuator within the gas cluster ion beam path for forming an attenuated sample of the gas cluster ion beam or for positioning said attenuator away from said gas cluster ion beam path for allowing workpiece processing by the un-attenuated gas cluster ion beam;

cluster ion beam current measurement means for measuring a current, I, of said attenuated sample of the gas cluster ion beam;

particle flow rate measurement means for measuring a particle flow rate, Γ, of said attenuated sample of the gas cluster ion beam;

average mass per charge measurement means for measuring an average mass per charge, $\left(\frac{m}{q}\right)_{average}$, of cluster ions in said attenuated sample of the gas cluster ion beam;

spectrometer means for measuring an average energy per charge, $\left(\frac{E}{q}\right)_{average}$, of the cluster ions in the attenuated sample of the cluster ion beam;

calculating means for processing measurements of $\left(\frac{E}{q}\right)_{average}$, I, Γ, and $\left(\frac{m}{q}\right)_{average}$, to calculate a measure of an average mass, $\overline{m}$, of cluster ions in the gas cluster ion beam; and

control means for providing signals to said first and second controllable moving means for positioning the attenuator within the gas cluster ion beam path for making

average mass, $\overline{m}$, measurement and also for positioning the attenuator away from said gas cluster ion beam path and for scanning the workpiece through said gas cluster ion beam path for workpiece processing.

30. The apparatus of claim 29, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average mass, $\overline{m}$, of clusters in the gas cluster ion beam to control the production of the gas cluster ion beam to improve the workpiece processing.

31. The apparatus of claim 29, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average mass, $\overline{m}$, of clusters in the gas cluster ion beam to adjust the average mass, $\overline{m}$, of clusters in the gas cluster ion beam to a desired value.

32. An apparatus utilizing a gas cluster ion beam for processing a surface of a workpiece, the apparatus comprising:

a vacuum vessel;

a gas cluster ion beam source within the vacuum vessel for producing a gas cluster ion beam;

an accelerator for accelerating the gas cluster ion beam along a beam path;

workpiece holding means within the vacuum vessel for holding the workpiece for gas cluster ion beam processing;

first controllable moving means for selectively scanning said workpiece holding means and the workpiece through said accelerated gas cluster ion beam at a location along said beam path and for selectively removing the workpiece holding means and the workpiece from said gas cluster ion beam path;

a cluster ion beam attenuator within said vacuum vessel with second controllable moving means for selectively positioning said attenuator within the gas cluster ion beam path for forming an attenuated sample of the gas cluster ion beam or for positioning said attenuator away from said gas cluster ion beam path for allowing workpiece processing by the un-attenuated gas cluster ion beam;

cluster ion beam current measurement means for measuring a current, I, of said attenuated sample of the gas cluster ion beam;

particle flow rate measurement means for measuring a particle flow rate, Γ, of said attenuated sample of the gas cluster ion beam;

average mass per charge measurement means for measuring an average mass per charge, $\left(\frac{m}{q}\right)_{average}$, of cluster ions in said attenuated sample of the gas cluster ion beam;

spectrometer means for measuring an average energy per charge, $\left(\frac{E}{q}\right)_{average}$, of the cluster ions in the attenuated sample of the cluster ion beam;

calculating means for processing measurements of $\left(\frac{E}{q}\right)_{average}$, I, Γ, and $\left(\frac{m}{q}\right)_{average}$, to calculate a measure of an average energy, $\overline{E}$, of cluster ions in the gas cluster ion beam; and

control means for providing signals to said first and second controllable moving means for positioning the attenuator within the gas cluster ion beam path for making average energy, $\overline{E}$, measurement and also for positioning the attenuator away from said gas cluster ion beam path and for scanning the workpiece through said gas cluster ion beam path for workpiece processing.

33. The apparatus of claim 32, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average energy, $\overline{E}$, of clusters in the gas cluster ion beam to control the production of the gas cluster ion beam to improve the workpiece processing.

34. The apparatus of claim 32, wherein the gas cluster ion beam source is a controllable gas cluster ion beam source and wherein the control means uses the measure of the average energy, $\overline{E}$, of clusters in the gas cluster ion beam to adjust the average energy, $\overline{E}$, of clusters in the gas cluster ion beam to a desired value.